Particle size effect on the elevated temperature wear behavior of SiC_p/Cu composites

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Discontinuously reinforced copper matrix composites exhibit integrative performances of good mechanical properties, high electrical and thermal conductivity, as well as low coefficient of thermal expansion [1–3]. Therefore, this class of material has received particular interest in many applications where high conductivity and wear resistance are required. Examples include continuous casting mold, electrodes of resistance welding, and the nozzle of CO_2 gas shielded arc welding. These components often operate at high temperatures over 1773–1873 K [4], where there is a danger of rapid breakage due to excessive wear or even seizure. Previous works have shown that the characteristics of reinforcement remarkably influence the wear process of metal matrix composite (MMCs). Particle size is one of the important factors, however, different conclusions have been drawn from the reports on this issue. Some authors indicated that the wear resistance of MMCs was improved with increasing particle size [5, 6], while others suggested that the increase of reinforcement size had negative effect on wear property [7, 8]. This discrepancy may result from the diversity of the material's, fabrication condition and the wear testing methods. Furthermore, most of the studies were carried out in a room-temperature environment, where the wear mechanism was quite different from that in high temperature. The objective of this work is to investigate the effect of SiC particle size on the elevated temperature sliding wear behavior of SiC_p/Cu composites, thereby providing experimental instructions for the designing of high-wear-resistant composite.

The composite materials used were produced by a powder metallurgy plus hot extrusion method. The starting material for matrix was pure electrolytic copper powder with a mean size of 48 μm, while the average particle sizes of SiC powder were 2.5, 14 and 40 μm respectively. Copper powder was mixed with a calculated amount of SiC powder (10% volume fraction), cold compacted, and finally sintered in dissociated ammonia gas at 1093 K. Hot extrusion was performed at 1073 K with a ratio of 10 to increase the densification.

Bulk hardness was measured on a Brinell hardness tester. Room temperature tensile tests were performed on a Shimadsu AG-100 kNA testing machine. Sliding wear tests were carried out by using an MMU-5G high-temperature-wear machine, on which the composite plate slid against the bottom surface of a GCr15 type bearing steel cylinder with a bulk hardness of HRC62 ± 2. Prior to testing, all the contacting surfaces were polished, cleaned in acetone in an ultrasonic cleaner, and finally dried. A normal load of 45 N together with a sliding speed of 0.15 m/s were used in this investigation. A standard test run for 45 mins was conducted, which corresponds to a sliding distance of 405 m. The tests were conducted at a temperature range of 298 to 693 K. The wear losses of the specimens were measured in an electronic balance of 0.1 mg precision. The worn surfaces of the composite specimens and wear debris were examined on a scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) analyzer.

Table I lists the results of room temperature tensile tests of different particle size. It is clear that the strength and hardness of the composites increase with decreasing SiC size. The yield strength and ultimate strength of the $SiC_{(2.5\mu m)}/Cu$ composite reach 137.3 and 212.6 MPa, which are 38.0 and 25.1 MPa higher than those of the $SiC_{(40\mu m)}/Cu$ composite, respectively. However, it should be pointed out that the ductility of composites turn worse as particle size decreases.

The specific wear rates of the SiC_p/Cu composites are plotted against the environmental temperature in Fig. 1. It can be seen that to a given composite, the wear rate decreases slowly with the temperature (called mild wear), and then increases abruptly at certain temperature range (called severe wear). For the mild wear, when the temperature is lower than 473 K, the wear rate of the $SiC_{(2.5\mu m)}/Cu$ composite is the highest, while that of the $SiC_{(14\mu m)}/Cu$ is the lowest. The composites with average SiC size of 40 and 14 μm transit to severe wear near the critical temperatures of 573 and 603 K respectively. Compared with the above two specimens, the $SiC_{(2.5\mu m)}/Cu$ composite exhibits lower wear rate when the temperature is higher than 673 K. Thus it can be seen that the effect of particle size on the wear resistance of SiC_p/Cu composites depends on the environmental temperature. In high-temperature sliding condition, fine particulate reinforcement is more effective in improving the wear resistance and alleviating the degree of severe wear.

Fig. 2 illustrates the typical worn surface morphologies of the copper matrix composites reinforced with

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TABLE I Room-temperature mechanical properties of SiC_p/Cu composite reinforced with SiC particles of various sizes

Particle size (μm)	Hardness (HB)	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (Gpa)	Elongation (%)
2.5	87.2	137.3	212.6	117.3	10.0
14	78.1	102.2	189.1	113.0	11.9
40	70.6	99.3	187.5	110.7	20.4

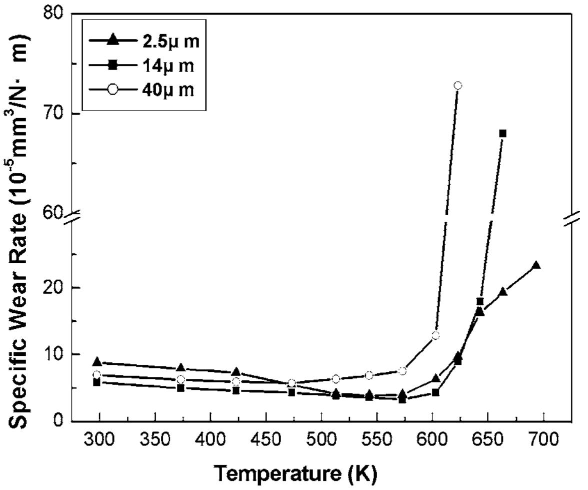

Figure 1 Variations of wear rates with temperature for SiC_p/Cu composites with different SiC particulate size.

SiC particles of 2.5 and 40 μm when tested at 623 K. To the $SiC_{(2.5\mu m)}$/Cu composite, most of the worn surface is covered by a smooth and compacted tribolayer (Fig. 2a). Along the sliding direction, there are some flat pits which may be the traces of tribolayer desquamation. In the case of the $SiC_{(40\mu m)}$/Cu composite, however, the worn surface is mainly composed of irregular grooves which are quite wide and deep (Fig. 2b). The edges of some grooves have been lifted, indicating the severe deformation of the worn surface at this temperature. Some little black pits were also found in the grooves. It is shown to be a broken SiC particle when observed at high magnification (the figure inserted at the top right corner). Much transferred material can be found on the corresponding counterfaces, implying the occurrence of adhesive wear.

Wear debris was collected after wear tests at 623 K and subjected to SEM observation. In general terms, it was found that decreasing the SiC size resulted in the formation of finer debris (Fig. 3). The wear debris of the $SiC_{(2.5\mu m)}$/Cu composite was in near equiaxed shape, with diameter less than 50 μm (Fig. 3a). In contrast, to the $SiC_{(40\mu m)}$/Cu composite, the wear debris mainly consisted of thick plank-like particles with lengths ranging from 50 to 200 μm (Fig. 3b). The scale of the surface deformation was considerably higher than the former, indicating the severe damage of the subsurface region at this temperature.

According to the strain gradient-strengthening law for particle reinforced MMCs [9] and the average edge-edge spacing between particles [10], the strengthening rate is given as:

$$\left(\frac{\sigma_c}{\sigma_m}\right)^2 = 1 + \beta l \frac{2\varepsilon}{d_p\left(\sqrt{\frac{2\pi}{3f_p}} - \frac{4}{\pi}\right)} \qquad (4)$$

where σ_c and σ_m are the flow stress of the composite and the matrix, β is a constant factor, ι is the characteristic microstructural scale, ε is the strain of the matrix sample when subjected to a uniform compressive loading.

Hence, for a given copper matrix composite of certain SiC particulate fraction, the strengthening effect completely depends on the particle size. Decreasing particle size results in higher strain gradient and thereby better reinforcing effect. This theoretical analysis agrees well with the tensile test results listed in Table I, and is also applicable in high temperature deformation process. Consequently, fine SiC particles are more effectual in restricting the plastic deformation of subsurface region so as to improve the wear resistance of composite materials. However, the deepness that the fine SiC (i.e., 2.5 μm) can embed in the surface layer is small, so they are prone to be removed together with the surrounding copper matrix when the counterface asperities plough up the surface materials. The detached composite debris may adhere to the counterface and

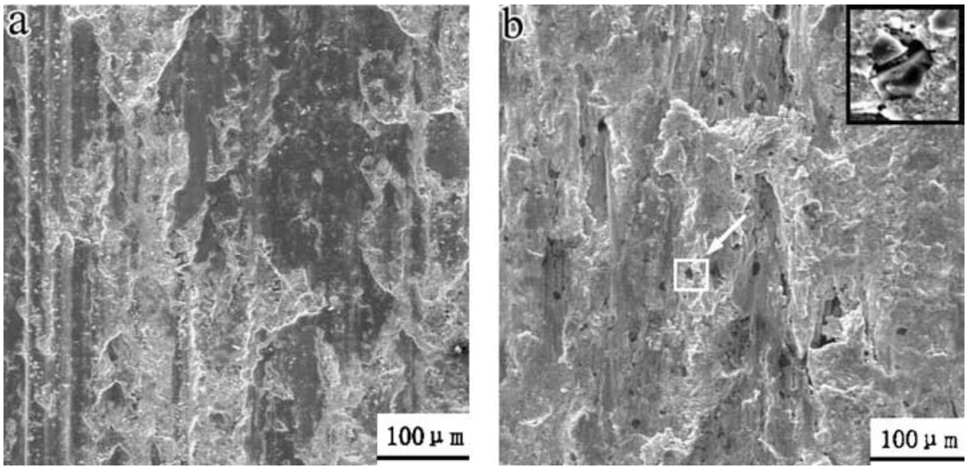

Figure 2 SEM images of the worn surfaces of the SiC/Cu composites tested at 623 K: (a) SiC: 2.5 μm and (b) SiC: 40 μm.

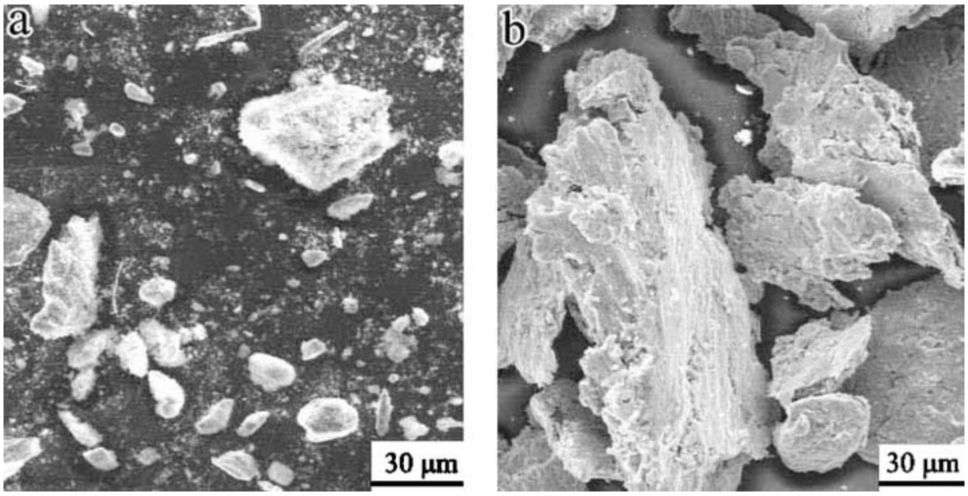

Figure 3 SEM morphologies of the wear debris formed at 623 K: (a) SiC: 2.5 μm and (b) SiC: 40 μm.

the contacting mode is changed to congeneric friction of SiC_p/Cu against SiC_p/Cu. Therefore, adhesive wear takes place at some regions, which results in the higher wear rate of $SiC_{(2.5\mu m)}$/Cu composite in the relatively low temperature range (Fig. 1).

With the raise of environmental temperature, the plastic deformation in near surface region increases gradually. According to the deduction of Alpas *et al.* [11], coarse reinforcement is easier to fracture in the wearing surface. In addition, the high-temperature mechanical properties of coarse particulate reinforced composite are low. Consequently, the composite would undergo severe wear when the environment temperature is high enough to cause shear instability and adhesive transfer. As for the $SiC_{(2.5\mu m)}$/Cu composite, however, few SiC fracture in the high temperature wear process, so they can act as load-bearing components to restrain the plastic deformation of the copper matrix at high temperature. Thus a compact-and-hard protective tribolayer may form on the worn surface, in a mechanism similar to that suggested by Stott [12]. In other words, with the decrease of SiC particle size, the triblolayer may exist stably at higher temperature, and the critical transition temperature of severe wear is also increased.

In conclusion, the effect of particle size on the wear properties of composite materials depends on environmental temperature. Coarse particles can protect the matrix from rubbing by the counterface at lower temperature. Fine particles are more effective in improving the high temperature mechanical properties of composites, consequently providing a more stable underlay for the tribolayer and improving the high temperature wear resistance.

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